

Search For Rapid X-ray Variability from the Black-Hole Candidate GRO J1655-40

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ABSTRACT

We have examined fifteen days of CGRO/BATSE data, obtained during the first outburst of the black-hole candidate source GRO J1655–40, to search for rapid variability of its X-ray flux. We find no evidence for significant variability of GRO J1655–40 during our observations, with a 2σ upper limit to the fractional r.m.s. amplitude in the frequency range 0.03–0.488 Hz of 6.6%. We cannot, on the basis of our observations, determine the source state (low, high, or very-high state) of GRO J1655–40.

Subject headings: stars: individual (GRO J1655–40) — X-rays: stars

1. Introduction

The X-ray transient source GRO J1655–40 (also known as X-ray Nova Scorpii 1994) was discovered with BATSE on the Compton Gamma Ray Observatory on 27 July 1994. The evolution of the hard (20–100 keV) X-ray intensity during the subsequent 5 months has been discussed by Harmon et al. (1995). Three outbursts were observed, each characterized by a fast (< 1 day) rise to a level of 600–700 mCrab in the 20–100 keV range, with no well-defined single maximum during the outbursts (10–50 days). Typical peak flux levels were $0.30 \text{ photons cm}^{-2} \text{ sec}^{-1}$ in the energy range of the observations. There was no significant emission from the location of GRO J1655–40 for a 50 day period prior to 27 July.

GRO J1655–40 is a nearby (2–3 kpc) dynamical black-hole candidate with a reported mass function of $3.35 \pm 0.14 M_{\odot}$ (Bailyn et al. 1995a,b; see Tanaka & Lewin 1995 for a recent review of black-hole candidates). The source shows strong radio outbursts associated with superluminal expansion events (Tingay et al. 1995; Hjellming & Rupen 1995) that are correlated with the increase in hard X-ray flux. Bailyn et al. (1995b) found that the optical light curve shows eclipses, at an orbital period of 2.6 days, and suggested that the orbital inclination of GRO J1655–40 is close to 90° . The energy spectrum can be well described by a power law out to at least 300 keV, with spectral (photon) index varying between 2.5 and 3.1 (Wilson et al. 1995).

Here we report on the analysis of the fast variability of the hard X-ray intensity of GRO J1655–40. In section 2 we describe the observations and data analysis. We discuss our results in section 3. Section 4 summarizes our conclusions.

2. Observations

We used the 1.024 second time resolution count rates from the BATSE Large Area Detectors (LADs) in 2 energy channels corresponding to the energy range 20–50 and 50–100 keV (Fishman et al. 1991). Intervals were selected of 512 time bins (524.288 seconds) without interruptions or data drop-outs, during which GRO J1655–40 was above the Earth horizon. Our chosen segment length is a compromise between the number of contiguous segments that could be obtained (this is determined by incomplete data coverage, and SAA passages) and frequency resolution. We used data only from detectors in which the source was seen at an angle of $< 60^\circ$ from the detector normal. The segments were quadratically detrended, the resulting time series converted to power density spectra (PDS), and the PDS averaged over an entire day. Approximately 45 intervals were obtained each day during the outbursts. We have determined that for the purposes of this analysis quadratic detrending is equivalent to a detailed background model subtraction as described by Rubin et al. (1993). Using similar intervals obtained when the source was occulted by the Earth (approximately 29 per day) we verified that the PDS of the detector background counting rate is flat down to at least 0.03 Hz.

The data set that we could use is constrained by the presence of other potential noise sources in the field of view of the uncollimated LAD detectors that are facing GRO J1655–40. Cygnus X-1 is a persistent source that shows strong variability in the frequency interval of interest. Because of the large angle ($\sim 86^\circ$) between Cygnus X-1 and GRO J1655–40, it is possible to choose detectors that face GRO J1655–40 in which Cygnus X-1 is at an angle $> 90^\circ$ from the detector normal. Only these detectors have been used in the following analysis. The soft X-ray transient source GX 339–4 (located within 10° of GRO J1655–40) was found from the source monitoring by BATSE through daily occultation analysis (Harmon et al. 1993) to be bright during the second and third

outburst of GRO J1655–40. We have therefore confined our observations to the 15 days corresponding to the first outburst when no other sources in the vicinity of GRO J1655–40 were detected with BATSE at a level higher than $0.16 \text{ photons cm}^{-2} \text{ sec}^{-1}$, and when the daily averaged flux of GRO J1655–40 was higher than $0.19 \text{ photons cm}^{-2} \text{ sec}^{-1}$ (28 July 1994–11 August 1994). Figure 1 shows the flux levels for this interval (Harmon et al. 1995).

The analysis is complicated by the existence of background noise in the LAD detectors that is likely due to weak unresolved sources in the uncollimated field of view. Figure 2 shows the power levels normalized to a Poisson level of 2.0 (Leahy et al. 1983), and averaged over the frequency interval 0.03–0.488 Hz in detectors facing the region of GRO J1655–40 for 16 days prior to the outburst. During this period, no transient sources with a hard spectrum and known fast variability were detected with BATSE in this region having a flux greater than $0.2 \text{ photons cm}^{-2} \text{ sec}^{-1}$ (20–100 keV). The 16 day average of the (0.03–0.488 Hz) power density is 2.035 ± 0.007 .

Figure 3 shows the averaged PDS for GRO J1655–40 during the interval 28 July 1994 to 11 August 1994, corrected for the background noise effect described above. The power density was normalized to represent the squared fractional r.m.s. amplitude per unit frequency (see Van der Klis 1995 for the formulae). Figure 4 shows the (0.03–0.488 Hz) integrated daily averaged PDS measured from GRO J1655–40, where the PDS have been normalized in the same way as in Figure 3. The errors have been propagated from the variance per bin calculated for each daily average, the errors in the subtracted background power, and the count rate errors derived from occultation analysis.

The average value of this squared fractional r.m.s. amplitude equals $(0.6 \pm 1.9) \times 10^{-4}$ (r.m.s./mean)²; the 2σ upper limit to this quantity equals 4.4×10^{-4} . The corresponding 2σ upper limit to the fractional r.m.s. amplitude, f , averaged over the 15 days of observation equals 6.6%.

3. Discussion

Based on their spectral and fast-variability properties, it appears that the black-hole X-ray binaries have three states, the ‘low’, ‘high’ and ‘very high’ states (Miyamoto et al. 1994; Van der Klis 1994a). The high state is characterized by the presence of a strong ultrasoft component which dominates the 1–10 keV X-ray flux. Since no low-energy X-ray observations were made during the period covered by our study, we cannot make a statement on the source state of GRO J1655–40 on the basis of its spectral characteristics.

In the low state the X-ray spectra of black-hole X-ray binaries are very hard, and well described by a power law that extends up to several hundreds of keV. The PDS is characterized by a power law at high frequencies, with an approximately flat part below a variable ‘break frequency’ ν_b . In PDS that are normalized according to Belloni & Hasinger (1990) the high-frequency part of the PDS does not change much; therefore, f , in a given frequency interval that contains the break frequency, is anticorrelated with ν_b .

If GRO J1655–40 had been in the low state during our observations, and followed the (ν_b, f) relation of Cygnus X-1 (Van der Klis 1994b; Crary et al. 1995) the break frequency would have to be at least ~ 0.7 Hz, to account for the observed upper limit to f of 6.6%. The required extrapolation of ν_b beyond the range observed for Cygnus X-1 (0.04 to 0.4 Hz) seems moderate enough that we cannot exclude that GRO J1655–40 was in the low state during our observations.

The high state of black-hole X-ray binaries is characterized by the presence of a strong ultra-soft spectral component, which dominates the flux in the 1–10 keV range. In the high state an anticorrelation is observed between the 2–10 keV source variability and spectral hardness, which has been interpreted as a dilution of the variability in the hard power law spectral component by the less variable ultrasoft component.

No information on the presence or absence of an ultrasoft component in the X-ray spectrum of GRO J1655–40 during our observation is available. If we assume that the total luminosity of GRO J1655–40 does not exceed the Eddington limit, then with the distance of 3.5 kpc (Bailyn et al. 1995a) and mass of at least $3.35 M_{\odot}$ we find that there is ample room for an ultrasoft component (the 2–100 keV luminosity in the power law component is only one third of the Eddington limit). We cannot, therefore, exclude that GRO J1655–40 was then in the high state. If it were, the low value of f we have observed would indicate that the variability of the hard (20–100 keV) power law spectral component is smaller in the high state than in the low state. This, in turn, would suggest that the low values of f observed in the 2–10 keV band in the high state is not only the result of the above mentioned dilution by the ultrasoft component, but that the variability of the power law component in this energy range is low as well.

The very high state (VHS) has so far only been observed in two sources, GS 1124–68 (Miyamoto et al. 1993) and GX 339–4 (Miyamoto et al. 1992). The X-ray spectrum then has, at least part of the time, a power law component above 20 keV. Miyamoto et al. (1994) have decomposed the PDS obtained with Ginga for GS 1124–68 in the VHS into a power law component and a ‘flat-topped’ component. The latter has a constant value of $\sim 0.001 \text{ Hz}^{-1}$ for frequencies below 1 Hz, and is independent of energy in the 1–37 keV range. This PDS level corresponds to a value for f in the frequency range 0.03–0.488 Hz of 3%. If we assume that the energy independence of the PDS in the VHS extends throughout the BATSE energy range, the observed variability properties of GRO J1655–40, presented here are consistent with the idea that the source was in the VHS during our observations.

4. Conclusions

During the first outburst of GRO J1655–40 we detected no (0.03–0.488 Hz) variability in its (20–100 keV) flux, with an upper limit to its r.m.s. amplitude of 6.6% (2σ). Several bright (≥ 1 Crab, 20–100 keV) black-hole candidate sources observed with BATSE (in particular, Cygnus X-1, GRO J1719–24, and GRO J0422+32) have shown enhanced noise power in the 0.03–0.488 Hz range, and occasional quasi-periodic oscillations (Kouveliotou 1994; Van der Hooft et al. 1995). Fractional r.m.s. values for this noise observed from Cygnus X-1 (10–30%, Cray et al. 1995) and GRO J1719–24 ($\sim 15\%$, Van der Hooft et al. 1995) are characteristic of the low state (Van der Klis 1994), and it is likely that they were encountered in that state with BATSE.

Based on the BATSE data for the period July 28–August 11, 1994 alone we cannot interpret the observed low variability of GRO J1655–40 in terms of the source state scheme for black-hole candidates. For that a better understanding of the hard X-ray properties of black-hole candidates (e.g., their spectral slope) in the different source states is required. Investigations of this type will be facilitated by low-energy (< 10 keV) observations, performed concurrently with a BATSE observation.

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Fig. 1 – Hard X-ray light curve (20-100 keV) for GRO J1655–40 from TJD (= Julian Day – 2440000.5) 9560 (1995 July 27) to 9585 (1995 August 21) obtained with BATSE occultation analysis.

Fig. 2 – Average power per bin for detectors facing the region of GRO J1655–40 for 16 days prior to discovery. The power has been normalized such the Poisson level is 2.0. The average taken over the interval 0.03–0.488 Hz is 2.035 ± 0.007 , shown by the dotted line.

Fig. 3 – Averaged (1995 July 28–1995 August 11) PDS corrected for Poission fluctuations and background noise shown in Figure 2, normalized to fractional squared r.m.s. Hz^{-1} .

Fig. 4 – Calculated fractional squared r.m.s. (0.03–0.488 Hz) for GRO J1655–40 during outburst from TJD 9561 (1995 July 28) to 9575 (1995 Aug 11). Contributions to the background shown in Figure 2 have been subtracted from these data.

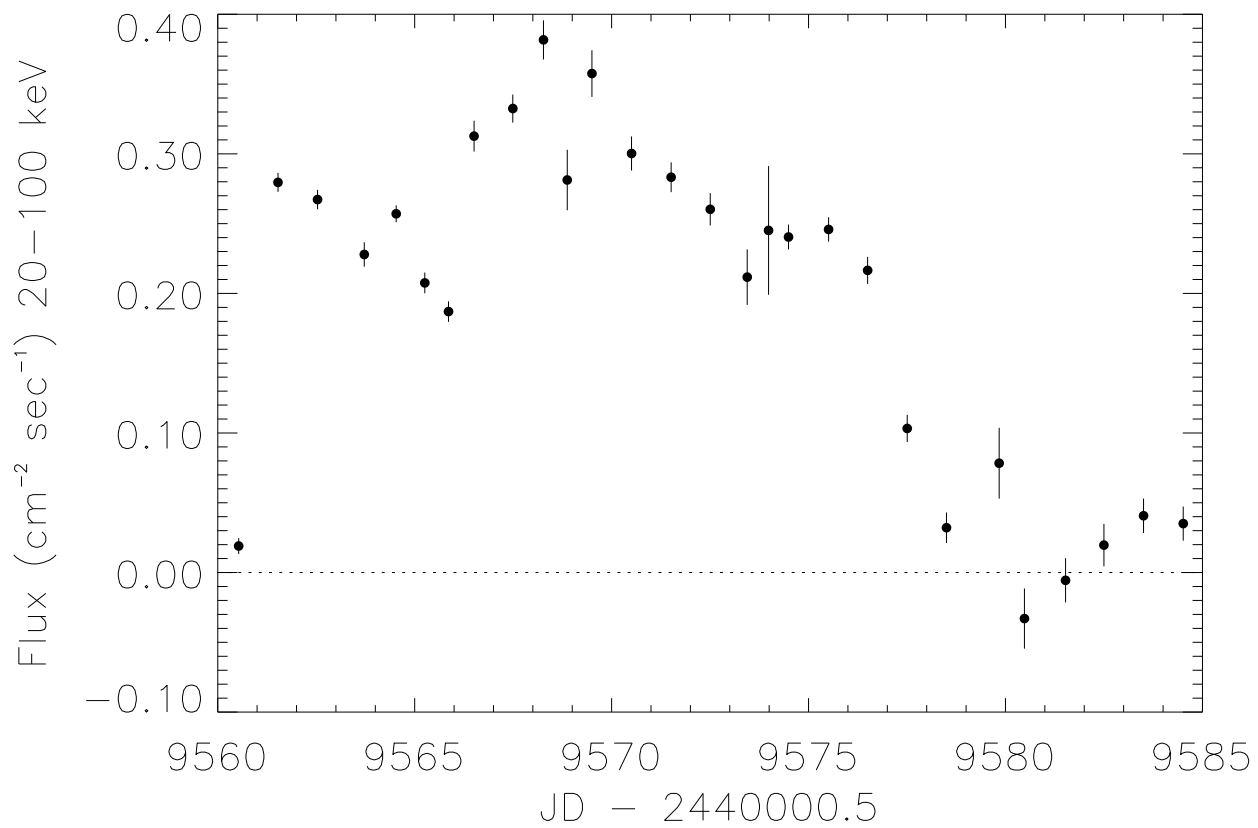


Fig. 1.—

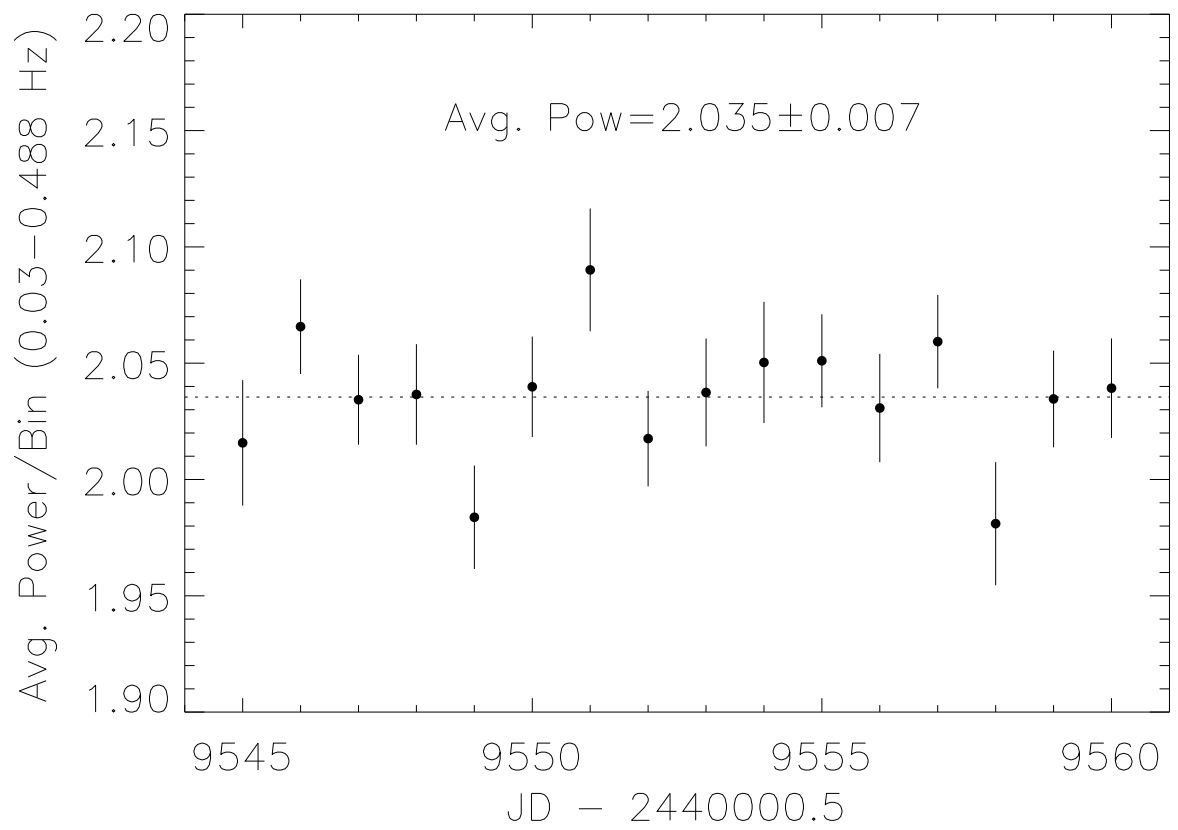


Fig. 2.—

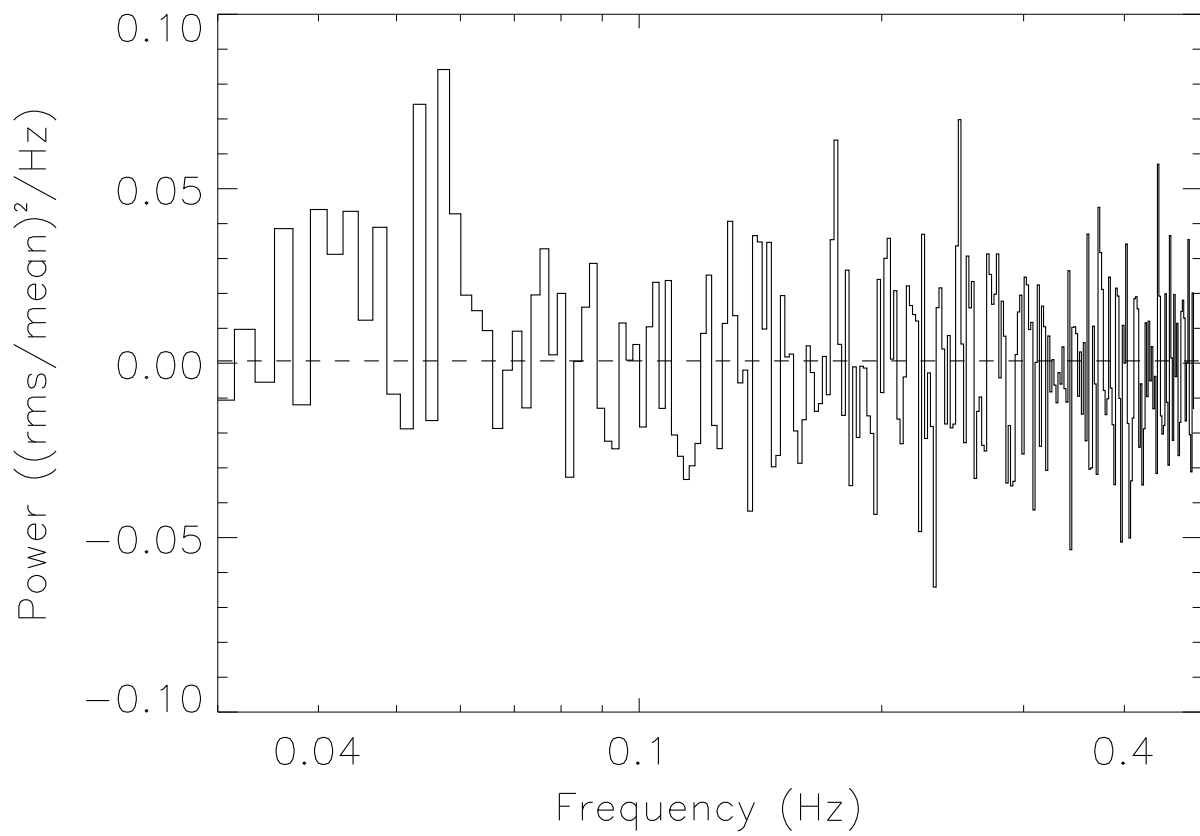


Fig. 3.—

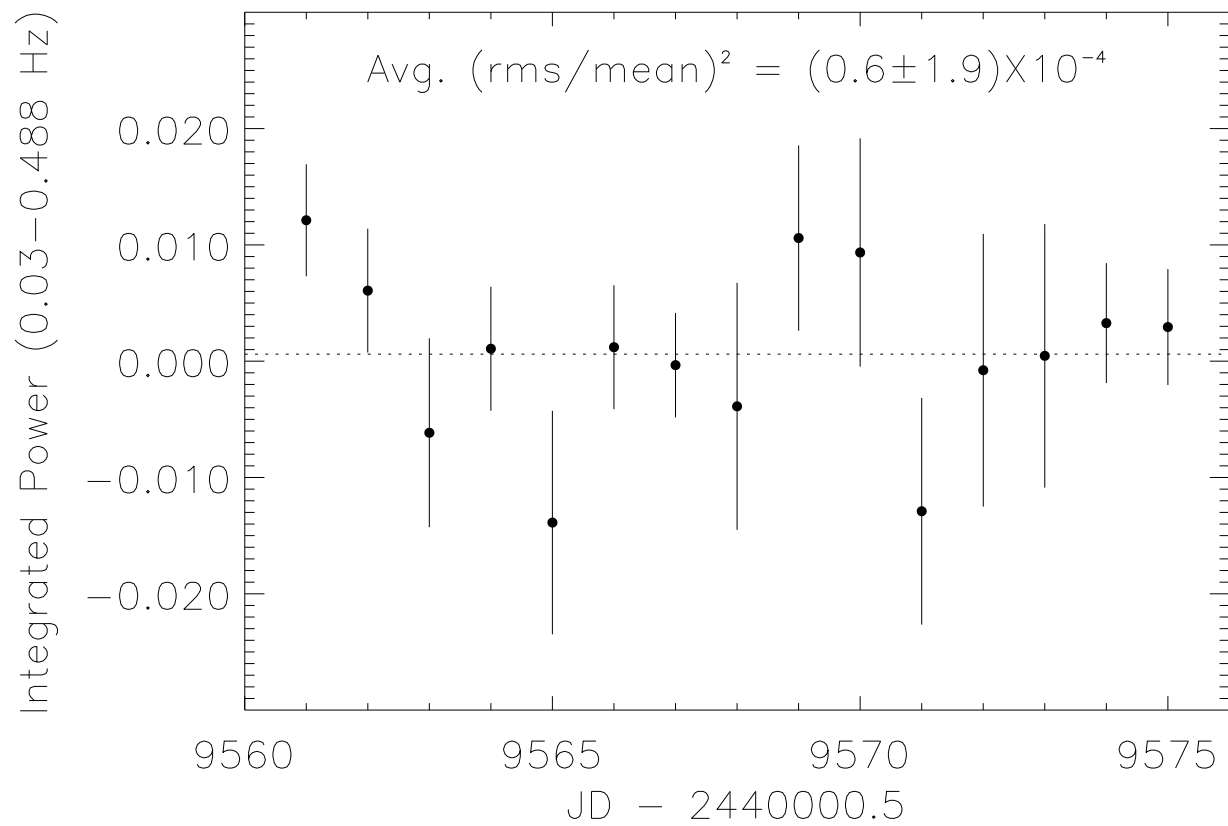


Fig. 4.—